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Mass Balance of Multiyear Sea Ice in the Southern Beaufort Sea

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LONG-TERM GOALS

1) Determination of the net growth and melt of multiyear (MY) sea ice during its transit through the southern Beaufort Sea
2) Identification of key regional processes in southern Beaufort Sea affecting MY ice recruitment
3) Improved predictability of the future states of the Arctic ice pack

OBJECTIVES

We have four main scientific objectives:

I) Estimation of MY ice volume entrained into the Beaufort Sea from north of Canada

The region north of the Canadian Archipelago contains some of the oldest and thickest ice in the Arctic and the amount of this ice imported into the Beaufort Sea has a significant effect on the overall MY ice budget of the Arctic.

II) Estimation of rate of thinning of MY ice during transit through southern Beaufort Sea

The thickness of MY ice at the end of its westward transit through the Beaufort Sea will have a critical impact on the volume of MY ice recruited from one year to the next and on navigability in the Beaufort and other marginal seas.

III) Assessment of contribution of refreezing of meltwater to overall mass balance of MY ice

Meltwater created through surface ablation can refreeze if it finds its way underneath the sea ice where the ocean will typically be at the colder freezing point of seawater. This can create ice lenses and false bottoms beneath the sea ice and make a positive, but poorly-understood, contribution to the mass balance

IV) Assessment of the role MY ice dispersal in promoting ice loss

We speculate that diminished MY ice in the Beaufort Sea may be a consequence of changes in drift patterns. Moreover, if net drift and divergence increase as MY ice extent decreases, this may represent a feedback process that will accelerate the Arctic's trajectory toward a seasonally ice free state.

APPROACH

To address our four main scientific objectives, we are employing a data fusion approach using a range of public-domain in-situ and remote sensing datasets. Through the methods described below, we aim to identify and quantify regional feedbacks between ice dynamics and mass balance, which will be critical in the predictability of ice conditions of timescales of 5-10 years.

Beaufort Sea flux gates (Hutchings and Mahoney)

As one step toward addressing objective I, we have analyzed buoy drift data to determine areal flux of sea ice entering and exiting the Beaufort Sea through "gates". This works build upon previous analysis by Hutchings and Rigor (2012) and is the subject of another paper currently in preparation by

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Petty et al. We will extend these results by combining them with satelite-derived ice age data (*Maslanik et al.*, 2007) to focus on the areal flux of multiyear passing through these gates. Deriving the volume flux of MY ice will be more challenging as observational ice thickness data are sparse. However, we will make use of airborne electromagnetic (AEM) data from the Tuktoyaktuk and Barrow regions to examine differences in the thickness of ice entering and leaving the southern Beaufort Sea, which will also address objective II.

Repeat passes of ice over moored IPSs (Mahoney)

In addition to the flux gate approach described above, we are also tracking changes in MY ice thickness in the southern Beaufort Sea (Objective II), through a combined Eulerian-Lagrangian approach that identifies cases when drifting ice makes multiple passes over moored ice profiling sonars (IPSs). In earlier work on this project, we analyzed data from the International Arctic Buoy Program (IABP) over the period 2003-2012, and identified 12 buoys that repeated passes within 30 km of one or more of four IPS-equipped moorings deployed as part of the Beaufort Gyre Exploration Project (BGEP). This demonstrates that such events are sufficiently commonplace to allow a Lagrangian analysis of ice thickness changes over time in the Beaufort Sea.

Analysis of melt processes from ice core and IMB data (Eicken)

Through stratigraphic analysis of sea ice cores collected from the Beaufort and Chukchi Seas as part of the Seasonal Ice Zone Observing Network (SIZONet), we identify annual layers that help constrain the age of the ice. In combination with ice drift data, this will allow us to estimate the origins of MY ice in the Beaufort Sea. Ice core samples that are brought back to shore were melted and used to determine profiles of salinity and stable isotope ratios. These data allow us to identify layers of refrozen melt water that once pooled beneath the ice. These meltwater layers, traces of which are found in all multiyear ice cores, form part of the annual accretionary layers and contribute to the total mass budget of level ice in the region. Identifying such layers will help interpretation of data from ice mass balance buoys (IMBs), which may overestimate ice thickness in the presence of false bottom or under-ice melt ponds. In addition, we can draw on mass balance data from Ice Mass Balance buoys (IMBs) to identify the potential impact of underwater ice formation on the seasonal mass budget. These analyses will be fundamental to achieving objective III.

Analysis of thickness changes in context of ice deformation (Hutchings)

Ice dynamics play a complex role in the overall mass balance of sea ice in the Beaufort Sea (e.g., *Hutchings and Rigor*, 2012). We expect to gain some insight into these processes (Objective IV) though analysis of the tails of ice thickness distributions corresponding to repeat overpasses of moored IPSs. However, it is not clear that the current observing assets are capable of resolving ice motion with sufficient fidelity to resolve to lead creation and ridging rates. With this in mind we are investigating the utility of remotely sensed ice drift products in providing deformation fields. We used divergence and shear from drifting buoy arrays to ground truth two representative satellite-derived ice velocity products: the Radarsat Geophysical Processor System (RGPS; *Kwok*, 1998) and the daily gridded ice velocity product produced by Fowler *et al. (2013).* These products allow us to investigate the effects of sampling rate, position accuracy and spatial resolution on the ability to monitor sea ice deformation. Following Lukovich *et al.* (2014), we are also developing approaches to map dynamical regimes along buoy tracks. These regimes range from super-diffusive conditions, where ice is advected and organized structures are preserved, to sub-diffusive, where ice-ice interactions dominate.

WORK COMPLETED

Dataset compilation

We have now largely completed compiling the collection of in situ and satellite datasets to be used in the approaches described above (Table 1). Newly added datasets this year include point-based timeseries of ice velocity from acoustic Doppler current profilers (ADCPs) co-located with the moored IPSs in some years and Lagrangian ice velocities from RGPS. We also incorporated the recently

updated version of Fowler *et al.*'s gridded ice velocity product (*Fowler et al.*, 2013), which we refer to as the FGIV dataset.

In addition, we have developed software tools for combing these data, such as the generation of psuedo-spatial series from timeseries of IPS and ice velocity data and the extraction of ice thickness distributions corresponding to specific overpasses.

Table 1: Datasets compiled to date

Geophysical data type	*Source*	*Time period acquired*
Buoy tracks	IABP	12 hrly position data 1978-2012
Ice thickness	SIZONet	April campaigns 2007-13
Ice thickness	BREA	April campaigns 2012-13
Ice draft	BGEP	2003-2012
Ice velocity (ADCP)	BGEP	2005-2011
Ice velocity (FGIV, v2)	NSIDC	1978-present
Ice velocity (RGPS)	NASA	1996-2007
Sea ice concentration	NSIDC	1978-present
Aerial photography	NASA	Arctic sea ice flights 2011-12
Ice core data	SIZONet	April campaigns 2007-13
Ice mass balance buoys	IABP/CRREL	1993-2012

Pseudo-Lagrangian numerical buoys

To expand the number of repeat-pass events to analyze we have recently explored the possibility of using Eulerian FGIV data to "deploy" a large number of numerical pseudo-Langrangian buoys at each mooring location. Figure 1 shows "pseudo-plumes" originating from each of the four BGEP moorings over a 210-day period, indicating advection of ice between moorings. The saturation of each color indicates the number of numerical buoys occupying each grid cell, with whiter shades indicating higher concentrations.

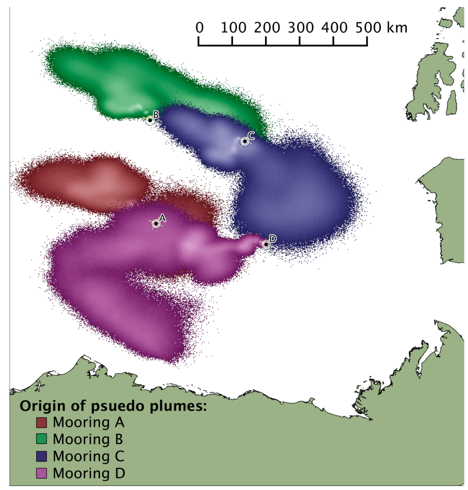

Figure 1: "Pseudo-plumes" of ice originating from the locations of four moored IPSs. Each colored plume represents the positions as of December 31, 2004, of 10,000 numerical buoys initiated daily at a mooring location over a 210-day period.

Cross-validation of ice thickness and velocity data

The fusion of ice thickness and velocity is critical to our approaches for addressing objectives I and II. For the flux gate analysis we are combining drift data from buoys and satelites with thickness data from AEM surveys, while for the repeat-pass analysis we are also using ice velocity data from moored acoustic Doppler current profilers (ADCPs) and ice draft data from IPSs. Analyzing coincident data from an AEM overpass of an IPS near Barrow in April 2010 (*Mahoney et al.*, 2014, in press) we found these different methods can be reconciled provided accurate ice velocities are available to convert the timeseries of IPS data into a pseudo-spatial series and appropriate filtering is performed to account for differences in sensor footprint size. In addition, in work currently being prepared for publication, we have made a similar comparison between ADCP- and FGIV ice velocities and found the latter to suitable for generating pseudo-spatial IPS series if ADCP are not available (as is the case for much of the BGEP IPS data set).

Analysis of ice core stratigraphy and IMB bottom data

To examine the role of refrozen meltwater in the mass balance of MY ice, we have examined salinity and $\delta^{18}O$ profiles from nine ice cores extracted from MY ice in the study region near Barrow, Alaska over the period 2007-2014. While we are still waiting for stable-isotope measurements to be completed several of these cores show some evidence of internal meltwater layers indicative of a combination of false bottoms and bottom meltwater infiltration (e.g., *Eicken et al.*, 2002). Moreover, information about the minimum age of the cores can be extracted from the stratigraphic data as well. In addition, we have made a careful analysis of ice bottom depth data from all IMBs (2000-2013) equipped to provide evidence of bottom melt/accretion rates.

RESULTS

Areal fluxes in to and out of the Beaufort Sea

Having expanded the ice drift analysis of Hutchings and Rigor (2012) to represent fluxes in to and out of the Beaufort Sea from 1979 to present, we find the following:

- Fluxes of ice in to the northern and north-western Beaufort Sea are not unusual in recent years. There has been a tendency for large import to the north-eastern Beaufort from 2010-2013.
- There is an increase in export of ice from the southern Beaufort to Chukchi Sea. This is predominant in winter and spring since 2010.
- Unlike the 2007 ice loss event, we do not find subsequent summer low ice extents can be explained by transport of ice from the region.

Assessment of ice velocity data products for mapping ice deformation

Comparing strain rates estimated from RGPS and FGIV gridded ice velocity data with those calculated from buoy arrays, we find that:

- RGPS underestimates the magnitude and variance of divergence and shear rates.
- The FGIV product provides reasonable statistical and spectral representation of divergence and shear, but it performs poorly on cross-spectra analysis with drifting buoy data.
- Averaging data over space and time improves representation.

MY ice thickness changes from repeat IPS observations

Figure 2 shows the tracks of two IABP buoys that each made four passes over moored IPSs:

- Together these provide nearly continuous Lagrangian observation of the thickness changes of MY ice in the Beaufort Sea from December 2006 to August 2009.
- Ice distributions calculated for each overpass event are shown in Figure 3. The dots in Figure 3a-d indicate the ice draft measured at a nearby IMB, which was deployed in level MY ice.
- The agreement between IMB-derived draft and local maxima in the IPS-derive draft distributions supports the validity of these repeat observations
- Prior to the 2007 summer, these dots coincide with weak, but distinct secondary modes in the distributions
- In the early winter of 2007, the thickness of MY ice that survived the summer is indistinguishable from that of newly grown first year ice.
- The draft distributions for buoy 74360 exhibit no maxima thicker than the mode attributed to FY ice

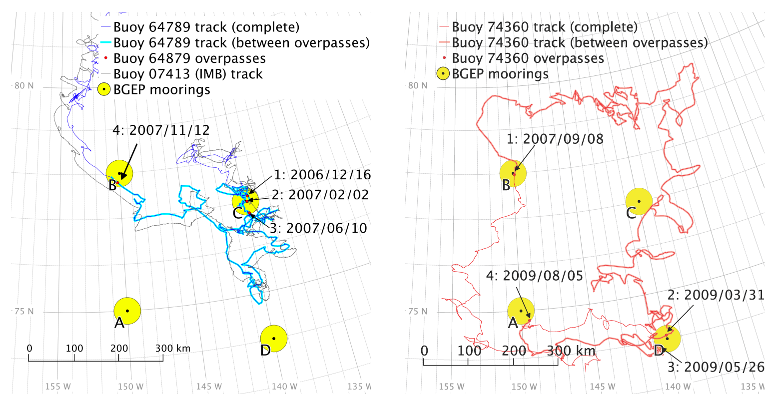

Figure 2: Tracks of two buoys making multiple overpasses over moored IPSs. a) Buoy 6879, which remained close to an ice mass balance buoy throughout its drift and b) Buoy 74360.

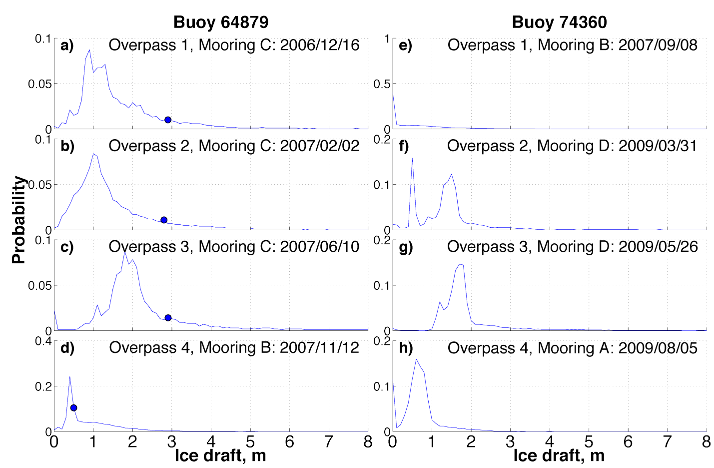

Figure 3: Ice draft distributions for each of the IPS overpasses shown in Figure 2

Meltwater contribution to MY ice mass balance

Through analysis of photographs and salinity and $\delta^{18}O$ profiles of nine MY ice cores collected near Barrow, between 2007 and 2014, we find that:

- Five cores exhibited one or more refrozen meltwater layers, up to 0.4 m thick (potential sixth core to be confirmed through pending stable isotope analysis)
- Cores collected between 2007 and 2009, exhibited a minimum age of 5 years, while those collected after 2009, exhibited minimum ages of between 2 and 4 years.
- We were not able to find MY ice within helicopter range of Barrow in 2013

In addition, analysis of IMB data revealed false bottom formation in 6 out of 32 IMBs, with freshwater/ice layers 0.1 to 0.7 m thick, though there was no evidence these persisted beyond the end of the melt season.

IMPACT/APPLICATIONS

We anticipate our future results will improve understanding of the fate of multiyear sea ice in an increasingly seasonal ice pack and lead to reduced uncertainty in sea ice forecasting. In particular, by quantifying the roles of specific processes on the mass balance of MY ice in the Beaufort Sea, our work will highlight where key areas of undertainty remain. In addition, we are developing new techniques to utilize sea ice velocity measurements to study Lagrangian processes with Eulerian observations such as mooring data. Our detailed analysis of gridded ice velocity data is improving our understanding of the limitations of current techniques for calculating sea ice deformation, which will inform the design of future efforts to map sea ice motion.

RELATED PROJECTS

PI Mahoney and co-I Eicken are leading the Seasonal Ice Zone Observing Network (SIZONet) project. Data from this project will provide additional calibration and validation data to interpret airborne electromagnetic induction and ice-profiling sonar from the region. The project also contributes ice thickness and ice core data sets analyzed in this study.

Co-I Hutchings is leading the NSF-funded project Sea Ice Deformation Observation with an AON, which is assessing the capabilities of the current Arctic buoy network to resolve sea ice deformation and designing a network of GPS-enabled buoys to short-timescale motion and deformation events.

PI Mahoney is participating in efforts funded by industry and the Bureau of Ocean Energy Management (BOEM) to deploy buoys on drifting ice in the Beaufort Sea, including specific efforts to track MY ice floes entering the Chukchi Sea.

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